

## Ground-based Gamma Ray Astronomy

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**Abstract:** This paper is the write-up of a rapporteur talk given by the author at the 33rd International Cosmic Ray Conference in Rio de Janeiro, Brazil, in 2013. It attempts to summarize results and developments in ground-based gamma-ray observations and instrumentation from among the  $\sim 300$  submissions to the gamma-ray sessions of the meeting. Satellite observations and theoretical developments were covered by a companion rapporteur [1]. Any review of this nature is unavoidably subjective, and incomplete. Nevertheless, the article should provide a useful status report for those seeking an overview of this exciting and fast-moving field.

**Keywords:** ICRC2013, gamma-ray astronomy.

### Introduction

Over the past decade, gamma-ray astronomy has risen to prominence as probably the most productive sub-field of astroparticle physics. This is due to the results of the current generation of ground-based and space-based instruments, which have provided the first sensitive view of the gamma-ray sky. The importance of the field was recognized at the 33rd International Cosmic Ray Conference (ICRC) in Rio de Janeiro, Brazil, by a modification to the organization of the program, which now includes dedicated gamma-ray sessions sub-divided into experimental (GA-EX), instrumentation (GA-IN) and theoretical (GA-TH) branches. Around 100 talks and more than 200 poster presentations were given in the gamma-ray sessions at the conference. This paper attempts to summarize some of the highlights from these, with a focus on ground-based gamma-ray observations and instrumentation. A companion paper by L. Stawarz will cover space and balloon-based gamma-ray observations, and gamma-ray astronomy theory [1]. A broad review of the field was also presented at the conference by J. Hinton [2]. Slides from the associated rapporteur presentation are also available for download from the conference INDICO site<sup>1</sup>.

At the time of the previous ICRC, held in Beijing in 2011, the TeV catalogue contained 132 sources. The 2011 conference saw a number of ground-based highlights [3]: the detection of the Crab pulsar above 100 GeV by VERITAS and MAGIC challenged models of high energy emission from pulsars [4, 5]. H.E.S.S. reported the likely detection of TeV gamma-ray emission from a globular cluster [6], and the first pulsar wind nebula outside of our own Galaxy [7]. The addition of Fermi-LAT data to ground-based measurements of the SNR RX J1713.7-39466 showed strong support for a leptonic origin [8], while the broad-band spectrum of Tycho's SNR favoured a hadronic scenario (although with much more limited statistics) [9]. Blazars dominated the extragalactic results, which were marked by a dramatically increased rate of new detections following the release of the first Fermi-LAT catalogue, and the development of strictly contemporaneous, broad-band datasets, aided by extensive cross-collaboration coordination and cooperation [3]. The major instrumentation development was the commissioning of the second 17 metre MAGIC telescope, from which first results were presented [10].

In the two years since Beijing, the field has further progressed, and new discoveries continue to be made. Figure 1 shows the TeV sky as of summer 2013, containing now 145 sources<sup>2</sup>. I will attempt to summarize some of the more exciting new scientific results in these proceedings, but a clear theme of the 2013 meeting was the commissioning of new instruments, the successful completion of major upgrades to many of the existing facilities, coupled with a dramatic ramp-up in development work towards the next generation of instruments. This bodes extremely well for the near, medium and long-term future of the field. I begin by summarizing the current instrumental status.

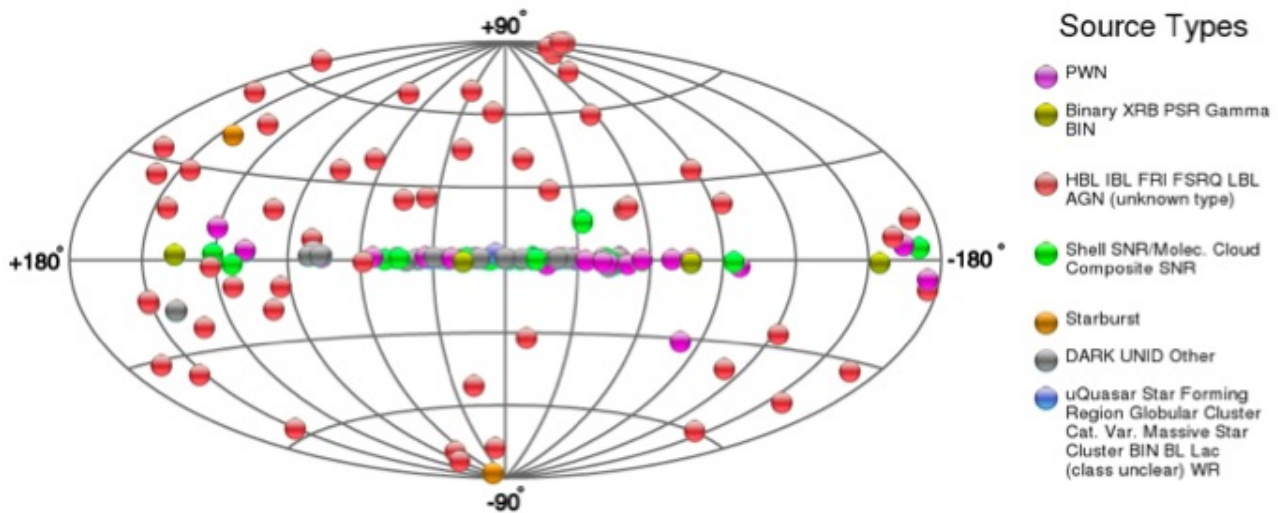
### Imaging Atmospheric Cherenkov Telescopes

Three major Cherenkov telescope arrays are operating around the world at present: VERITAS, H.E.S.S. and MAGIC, together with a number of smaller instruments. The three large facilities are all running smoothly, and have recently undergone major upgrades. The stereoscopic imaging technique they employ provides the highest sensitivity for gamma-ray astronomy from the ground, together with the best angular and energy resolution. Given the limited fields-of-view ( $\leq 5^\circ$ ), observations must be targeted, but the three arrays are distributed around the globe in such a way as to provide reasonable coverage of the entire sky. All provided detailed status updates in highlight talks at the ICRC [11, 12, 13] and I briefly summarize their status below, in an arbitrary reverse alphabetical order.

#### VERITAS

The VERITAS array of four 12 m diameter telescopes, located in Arizona, USA, has been in operation since the summer of 2007. Summer 2012 saw the completion of a program of major upgrades to the facility. These included the relocation of the initial prototype telescope to a more favorable location in the array (in 2009), and the installation of faster telescope-level trigger systems and a fiber-optic network (in 2011/12). A major development over the past

1. <http://143.107.180.38/indico/contributionDisplay.py?contribId=1310&sessionId=8&confId=0>  
2. <http://tevcat.uchicago.edu/>



**Figure 1:** The TeV source catalog in Galactic coordinates as of summer 2013, courtesy of TeVCat.

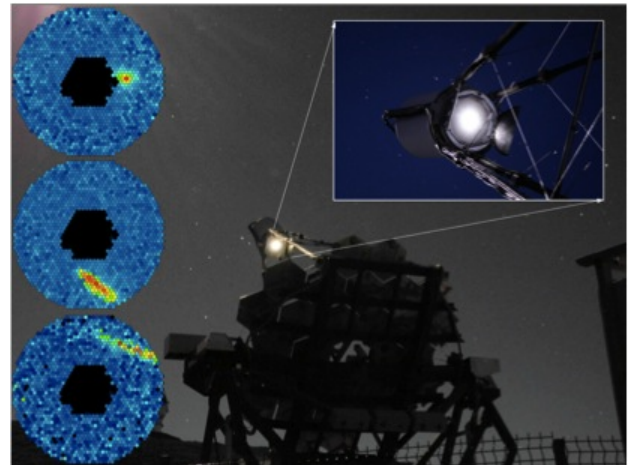
two years was the replacement of all of the telescope photodetectors with more sensitive, “super-bialkali” devices. This was completed in summer 2012, resulting in a 50% increase in the Cherenkov light yield, a 30% reduction in energy threshold and improved sensitivity, particularly for soft spectrum sources such as distant blazars [14, 11]. All of the VERITAS contributions to the conference are referenced on the arXiv in [15].

### MAGIC-II

MAGIC has been observing from La Palma since 2004, initially with a single 17 m diameter telescope, and, since 2009, with a stereo pair. Further upgrades have recently been completed [16], including the installation of an entirely new camera and trigger system for the original telescope, which now matches that of the second telescope and provides a homogeneous system [17]. The data acquisition system for both telescopes has also been replaced and standardized with a system based on the DRS4 chip [18]. The system is performing well, providing an integral sensitivity of  $0.71 \pm 0.02\%$  of the Crab Nebula flux for a 50 hour observation [19]. Future plans include the installation of an analog sum trigger system in fall 2013 for both telescopes, which will operate in parallel with the existing system and further lower the energy threshold [20].

### H.E.S.S. and H.E.S.S. II

The H.E.S.S. array of four, 12 m telescopes in Namibia was the first of the current generation of instruments to begin operations, and celebrated its 10th anniversary in 2012 [12]. The array has taken almost 10,000 hours of data, including 2,800 hours on a scan of the Galactic Plane [21]. The plane scan is now complete, and future observations will target individual objects. These studies will be greatly enhanced by the addition of H.E.S.S. II, a 614 m<sup>2</sup> telescope located at the centre of the array and equipped with a 2048-pixel photomultiplier tube camera (Figure 2). H.E.S.S. II is a technical *tour de force* - the largest Cherenkov telescope ever constructed - and the mechanical performance seems good [22, 23]. The collaboration presented first light at the ICRC, with a detection of the Crab Nebula [12].



**Figure 3:** Observations of cosmic ray events with the full moon in the centre of the FACT field of view [24].

### FACT

A relative newcomer to the field is FACT (First G-APD Cherenkov Telescope), located on La Palma and operating since 2011 [24]. As a single telescope with modest aperture (9.5 m<sup>2</sup>), FACT is scientifically limited to (useful) monitoring of the brightest TeV blazars [25]. However, it also serves as an important testbed for some of the technologies which will be employed in the next generation of Cherenkov instruments. The 1440 pixel silicon photodetector camera is the clearest example of this, and results confirming its stability and operation under bright moonlight conditions were presented [26, 27] (Figure 3). The telescope is also routinely operated remotely, with no need for on-site observers, with an ultimate goal of completely automatic, robotic operation [28].

### Non-imaging Cherenkov & Particle Detectors

Gamma-ray astronomy from the ground can also be performed by sampling the Cherenkov light pool with non-imaging detectors, or by measuring shower particles with



**Figure 2:** The H.E.S.S. II array in Namibia, showing the four original 12 m diameter telescopes and the newly commissioned 28 m diameter telescope in the centre [12]

detectors placed at high altitude. While the sensitivity, angular and energy resolution of these techniques are limited, in comparison with the imaging telescopes, this is offset by the extremely wide field of view (typically  $\sim 2$  sr) and, in the case of particle detectors, close to 100% duty cycle.

### ARGO-YBJ

The ARGO-YBJ experiment was a unique air shower detector consisting of a  $74 \text{ m} \times 78 \text{ m}$  carpet of Resistive Plate Chambers (RPCs) surrounded by a partially instrumented area out to  $100 \text{ m} \times 110 \text{ m}$ , located at Yangbajing (Tibet, China) at an altitude of 4300 m above sea level. Data-taking concluded after 5 years of observations in February 2013, with an integral sensitivity for the total dataset of  $\sim 25\%$  of the Crab Nebula flux [29]. Summary results were presented at the ICRC - one outstanding question remains the non-detection of the Milagro source MGRO J2019+37 by ARGO-YBJ, despite confirmation of this source with VERITAS, and the detection of other Milagro sources with ARGO-YBJ [30].

### Tibet-III

The Tibet air shower array also operates at Yangbajing, and consists of a high density array of over 500 scintillation counters with 7.5 m spacing, together with wider spaced outriggers. The array has been operating in various configurations since 1990, and provides an angular resolution of  $\sim 0.9^\circ$  at 10 TeV [31]. Results of a point source search for emission were presented, showing significant emission only from the Crab and Markarian 421 [32], together with some evidence for extended emission from Milagro sources [33]. Cosmic ray discrimination currently relies upon reconstructing the arrival direction of the particle shower, but the addition of large underground muon detectors is now in progress, and will allow discrimination based upon the shower muon content [34]. Data-taking with 5 of the planned 12 muon detectors will begin this year.

### HAWC

HAWC, the High Altitude Water Cherenkov observatory, is the successor to Milagro, currently under construction at 4,100 m above sea level on the Sierra Negra volcano in Mexico. The final array will consist of 300 water Cherenkov detectors, and provide order of magnitude improvements in sensitivity, angular and energy resolution over Milagro. 100 detectors had been deployed at the time of the ICRC, as illustrated in Figure 4 [35]. First results from the array



**Figure 4:** The High Altitude Water Cherenkov (HAWC) observatory on the Pico de Orizaba, with 100 tanks installed (one-third of the completed detector)

were shown, including measurements of the lunar cosmic ray shadow using 30 tanks [36] and the first evidence for a gamma-ray source from two weeks of 77-tank observations of the Crab Nebula [37]. Deployment and commissioning are ongoing, with science operations already underway, and completion of the full array is expected by the end of 2014.

### HiSCORE

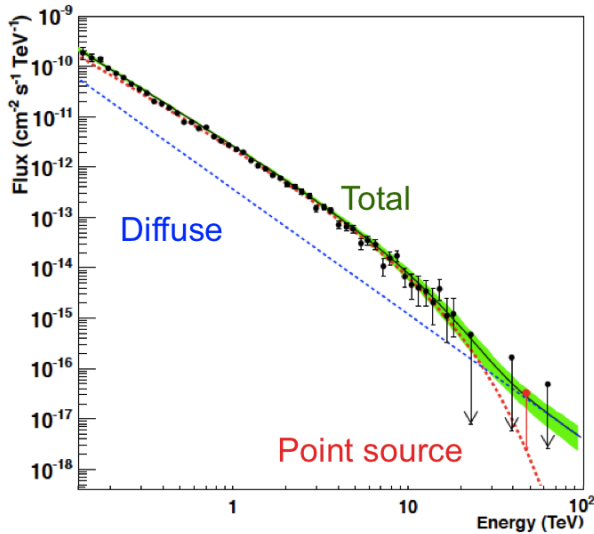
Contributions from the HiSCORE collaboration were included in the cosmic ray track at the ICRC [38] and so may have been missed by members of the gamma-ray community. However, the primary goal of this non-imaging Cherenkov detector is gamma-ray astronomy in the 10 TeV to several PeV range. A prototype array of three wide-angle (0.6 sr) optical stations has been deployed in the Tunka Valley near Lake Baikal, and technical tests are underway. The goal is to move towards a  $1 \text{ km}^2$  engineering array with 60 stations over the next two years.

## Results: Galactic Sources

### Galactic diffuse emission

While diffuse emission from the Galactic plane dominates the sky at  $< 100 \text{ GeV}$  energies, discrete sources are much more prominent at the higher energies probed with ground-based instruments. Milagro have reported the detection of a diffuse Galactic component, but a substantial fraction of this may be simply explained by the sum of a collection of





**Figure 5:** The results of a reanalysis of the Galactic Center TeV source, HESS J1745-290. Fitting the observed spectrum with diffuse and point source components lowers the point source spectral cut-off from 11 to 7 TeV.

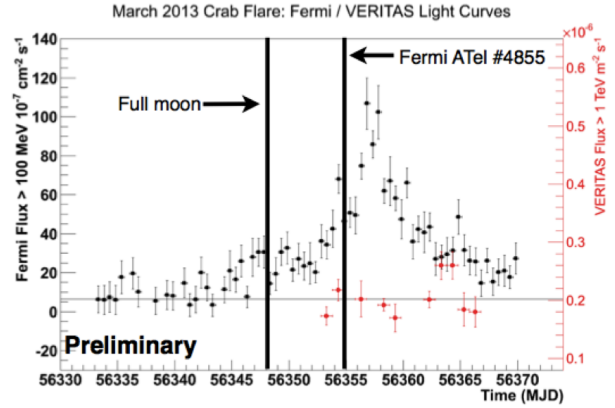
unresolved sources below the Milagro detection threshold [39]. In truth, the distinction between very widely extended sources and a diffuse background component is not strict. The ARGO-YBJ collaboration presented confirmation of the Milagro measurement at this ICRC [29]. H.E.S.S. have attempted to extract a truly diffuse background component from their Galactic plane scan, in an analysis which excludes any region containing a potential signal from the background estimation [40]. The remaining flux can be attributed to unresolved sources, and to cosmic ray interactions with diffuse matter and photon fields. Gamma rays from pion decay resulting from cosmic ray - matter interactions must comprise at least 25% of this diffuse flux. One conclusion to draw from this study is that, while the analysis is complex, imaging atmospheric Cherenkov telescopes are certainly capable of measuring widely extended and even diffuse sources, despite their limited field of view.

### Galactic Centre

The Galactic centre region hosts one known source of diffuse TeV emission, the result of cosmic rays interacting with high density molecular clouds along the Galactic centre ridge [41]. This diffuse component also contributes to the emission observed from the central point-like source in the direction of SgrA\*. A new analysis of the TeV point source was presented which attempts to remove this component, estimated at  $\sim 20\%$  of the total emission, which differs in spectral slope from the point source and displays no spectral cut-off [42]. Accounting for this significantly shifts the cut-off energy for the point source from 11 TeV to 7 TeV (Figure 5).

### The Crab Pulsar and Nebula

High energy studies of both the Crab Nebula and Pulsar have been reinvigorated in recently years following the discovery of a very high energy ( $> 100$  GeV) component to the pulsed emission, and variability in the “steady” flux at



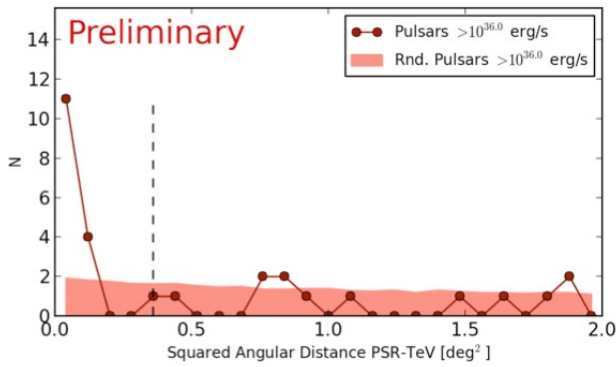
**Figure 6:** Fermi-LAT and VERITAS light curves for the March 2013 Crab Nebula flare. The baseline Crab Nebula synchrotron flux above 100 MeV and average VHE flux above 1 TeV are aligned, and are indicated by the solid black line. The vertical scales of both light curves have been adjusted such that the zero points and baseline fluxes are coincident.

lower energies. The most extreme example of this variability is in the Crab flares detected by AGILE and Fermi-LAT, in which the high-energy synchrotron flux from the nebula has been observed to increase by more than an order of magnitude. No new details on the pulsar were presented by ground-based instruments in the gamma-ray sessions, although some future exciting results were hinted at in the MAGIC highlight talk: in particular the fact that the pulsar peak widths (which are related to the geometry and size of the emission region) are exceptionally narrow at the highest energies [13].

At this conference, ground-based observations of the flaring Crab were presented by ARGO-YBJ, HAWC and VERITAS. ARGO-YBJ presented a re-assessment of their archival observations of the Crab [43], which shows some evidence for a persistent correlation between the ARGO and Fermi-LAT fluxes, and for a flux enhancement of a factor of  $2.4 \pm 0.8$  during bright flares. However, they conclude that the low statistical significance of these results does not allow to claim the detection of flux variability and requires a confirmation by more sensitive instruments [44]. In March 2013 the Crab flared brightly again, reaching 20 times the average steady synchrotron flux above 100 MeV [45]. HAWC was observing with 30 tanks operational, and saw no flux enhancement - they estimate that a 5-fold flux increase would have been detectable with  $5\sigma$  significance [37]. VERITAS observations during the flare also show no enhancement above 1 TeV [11], and constrain the variability at these energies to be less than 1% of that seen by the LAT (Figure 6).

### Other Pulsar Wind Nebulae

The Crab remains the only known source of pulsed gamma-rays above 100 GeV (indeed, the MAGIC Collaboration presented limits from an unsuccessful 75 hour search for pulsed emission from Geminga at this conference [46]). Pulsar wind nebula, however, are the most common class of Galactic TeV sources, which allows them to be subjected to broad population studies. The H.E.S.S. collaboration have begun such a study, using their Galactic plane scan



**Figure 7:** The number of high spindown energy pulsars, plotted as a function of their squared angular distance from a H.E.S.S. TeV source [47].

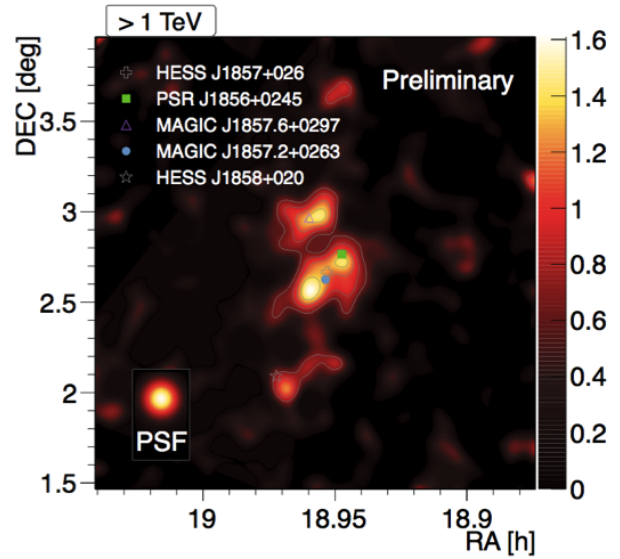
archive and comparing to pulsar characteristics in the ATNF pulsar catalog [47]. A consistent analysis has been applied at each pulsar location in order to derive fluxes and upper limits. This approach leads to a uniform selection and comparison of candidates, which should allow meaningful study of PWN properties and evolution. A simple first result of this study is the broad statement that high  $\dot{E}$  ( $> 10^{35} \text{ erg s}^{-1}$ ) pulsars tend to have TeV signals within  $0.5^\circ$  of their location - there are no spatial correlations beyond those expected from chance coincidence for less energetic pulsars (Figure 7).

Given their prevalence among TeV sources in the Galactic plane, coupled with emission spatially offset from the host pulsar location, PWN studies at TeV energies often involve a certain amount of detective work. Two particularly interesting “cases” were solved in presentations at this ICRC. MAGIC observations of HESS J1857+026 resolved this extended source into two components at energies above 1 TeV. One of these is likely the elongated PWN associated with the young energetic pulsar PSR J1856+0245. The other appears point-like, and remains unidentified [48] (Figure 8). VERITAS presented the results of a deep ( $\sim 50$  hour) observation of TeV J2032+4130 [49], the first unidentified source discovered at very high energies (by HEGRA [50]). The source is determined to be extended, with an asymmetric morphology which, in the context of multiwavelength observations of the same region, favours a PWN interpretation, associated with the LAT pulsar PSR J2032+4127.

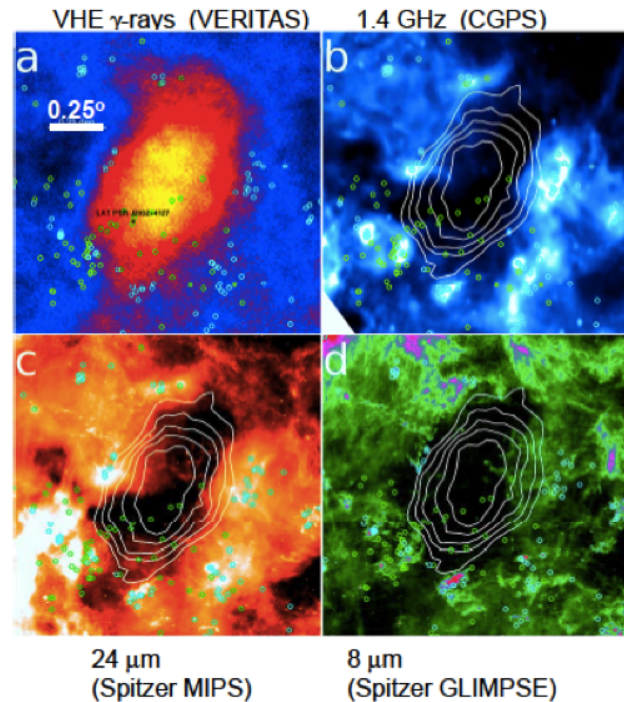
### Supernova Remnants

The most exciting result in gamma-ray supernova remnant (SNR) studies since the last ICRC is undoubtedly the discovery of direct evidence for the existence of hadronic cosmic ray particles in W 44 and IC 443, through the characteristic pion-decay signature in their sub-GeV spectra with Fermi-LAT [51]. However, the acceleration and escape processes are not yet well understood, and it is still far from clear whether particle acceleration in SNRs can explain the bulk of the Galactic cosmic ray population up to energies beyond the knee. Ground-based observations could help to resolve these questions, and supernova remnant results presented at the conference showed progress through some new discoveries and deeper studies of established sources, as well as initial results from an unbiased population study [52].

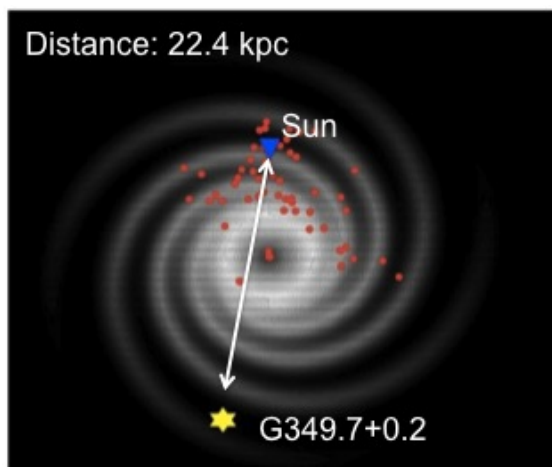
H.E.S.S. presented observations of a new TeV source



**Figure 8:** MAGIC gamma-ray flux map of HESS J1857+026 for events with estimated energy greater than 1 TeV, resolving the extended source into two distinct components [48].



**Figure 9:** The VERITAS skymap for TeV J2032+4130, along with radio and infra-red observations of the same region [49].

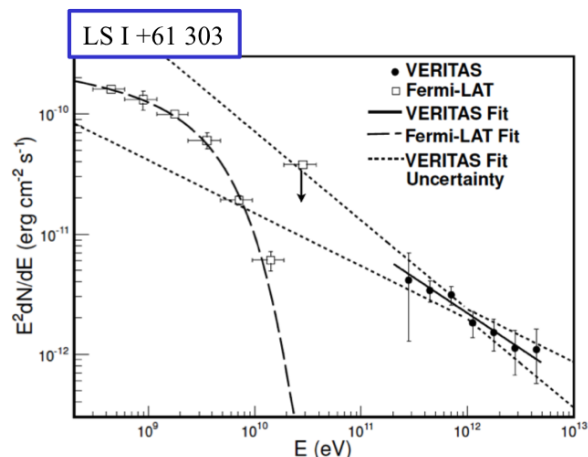


**Figure 10:** A cartoon showing the location in the Galactic disk of all known Galactic TeV sources (red), plus the newly discovered HESS source SNR G349.7+0.2 [53].

associated with the bright young SNR G349.7+0.2. The source received a deep exposure ( $\sim 100$  hours) as it shares the same field-of-view as RX J1713.7-3946, allowing a detection despite its location on the far side of the Galaxy (at a distance of  $\sim 22.4$  kpc) [53] (Figure 10). The emission is satisfactorily explained within a hadronic interpretation. H.E.S.S. also presented a reinterpretation of the most luminous Galactic TeV source, HESS J1640-465, which was previously identified as a likely PWN. The absence of an inverse Compton peak in the broadband gamma-ray spectrum, combined with a TeV morphology which overlaps with the northern rim of the SNR, now appears to favour hadronic emission from the SNR shell [54].

Resulting from a historical Type Ia progenitor supernova explosion, Tycho's SNR is a shell-type remnant expanding into the undisturbed interstellar medium. The relative simplicity of this system has made it a favorite choice for modellers, and the detection of TeV and GeV emission was shown at the last ICRC. In Rio, updated results from VERITAS extended the lower end of the spectrum to 300 GeV [55]. The statistical errors still accommodate a variety of different models (leptonic and hadronic, one- and two-zone), but data collection is ongoing. The W51 region, on the other hand, is a complex environment including a supernova remnant (W51C) interacting with the molecular clouds of the star-forming region W51B, as well as a PWN candidate. A TeV source in this region was originally detected by H.E.S.S. At this meeting, MAGIC presented the results of a 50 hour exposure which extends the spectrum, and appears to indicate that the majority of the emission in the region comes from the SNR-molecular cloud interaction [56].

Finally, an interesting (if speculative) search for gamma-ray emission associated with *very* young nearby *extragalactic* SNR was presented [57]. Such objects might possibly provide the source of particles to between the knee and the angle of the cosmic ray spectrum. A search for serendipitous H.E.S.S. observations of nearby ( $z < 0.01$ ) supernova locations within 1 year of the explosion yielded 9 candidates, but no detections.



**Figure 11:** The spectral energy distribution of LS I+61°303 from contemporaneous Fermi-LAT and VERITAS observations in 2011/2012, showing a distinct gap in the emission between 4 GeV and 300 GeV [59].

### Gamma-ray Binary Systems

The binary source class remains relatively small, at both GeV and TeV energies, but displays a rich phenomenology. The lightcurve of the only binary to be first discovered from the ground, HESS J0632+057 has now been measured over almost a decade's worth of 315-day orbits by VERITAS and H.E.S.S., showing close correlation between the TeV and X-ray flux, and including the first detection of TeV emission at phases outside of the bright X-ray flare phase [58, 59]. The measurement of variability in HESS J1018589 A now firmly associates this point-like component of an extended TeV source with 1FGL J1018.6-5856, the 16.6 day binary system discovered by Fermi-LAT [58].

LS I+61°303 is among the most heavily observed TeV sources in the northern hemisphere, but the results continue to surprise. New observations from VERITAS and MAGIC since the last ICRC show that the source has been bright at phases close to apastron for the first time since the launch of Fermi-LAT [59, 60]. This allows to construct a contemporaneous high-energy spectrum, revealing a sharp cut-off between the GeV and TeV spectra (Figure 11). The explanation for this "gap" in the spectral energy distribution (SED) is unclear, but it seems to indicate that the emission mechanism may be different in the GeV and TeV bands. The re-emergence of bright emission from LS I+61°303 also led to speculation that the high-energy emission may be modulated with the  $\sim 5$  year super-orbital period observed in X-ray and radio, which may be related to changes in the circumstellar disk of the Be star.

### Globular Clusters

The detection of GeV emission from numerous globular clusters by Fermi-LAT, and of TeV emission from the direction of Terzan 5 by H.E.S.S. [61], motivates the search for other members of this source class. Emission might originate from the combined emission of the numerous millisecond pulsars in the cluster cores, or from inverse Compton scattering of relativistic leptons accelerated in the cluster environment, for example close to the aforementioned millisecond pulsars. The Terzan 5 association is not definitive, primarily because the TeV source is slightly offset from the cluster center. The addition of another TeV/ cluster associa-



tion would make the identification much more compelling. Results of a search for TeV emission from 15 globular clusters were presented by H.E.S.S. [62], which revealed no new detections.

As a final point on Galactic sources, it is worth noting that one of the largest populations of TeV gamma-ray sources remains unidentified objects in the Galactic plane. For many of these, the search for a definitive counterpart is still ongoing, requiring ever deeper exposures and multi-wavelength detective work (e.g. [63, 49]).

## Results: Extragalactic Sources

### Blazars

The TeV blazar population continues to grow and, with the addition of five new members to the class announced in the run-up to this ICRC (KUV 00311-1938, PKS 0301-243, PKS 1440-389 [12]; H1722+119, MS 1221.8+2452 [13]), now numbers 49 sources. One development at the ICRC was the first presentation of broad-band blazar spectral energy distributions including data from NuSTAR, a focussing X-ray telescope launched in June 2012, which operates in the 3-79 keV energy range [64]. These observations, combined in coordinated campaigns with observations at lower and higher energies, now allow to characterize in great detail both the synchrotron and inverse Compton emission components of nearby blazars on a *daily* basis, even when the source is relatively quiescent. Prior planning is generally required for these campaigns, and so the fortuitous detection of a bright flare (exceeding 11 Crab in the TeV band) from Markarian 421 in April 2013 during multiwavelength observations is very exciting. Only preliminary results for an earlier part of the campaign were shown at the ICRC (Figure 12), and the interpretation is still in the earliest stages, but even these provide useful new information, including the absence of any evidence for a cut-off in both components of the SED.

More complete modelling has been applied to observations of Markarian 421 from an earlier, 2010, multiwavelength campaign, which captured a decaying flare from the source [65]. The authors model this with both one and two-zone synchrotron self-Compton emission models, and conclude that the evolution of the SEDs favours the presence of two 'blobs' of material, rather than the single blob typically used to describe flares in TeV blazars. A summary of H.E.S.S. observations of blazars similarly concluded that simple one-zone SSC models rarely provide a satisfactory fit to the complete SED, and are also unable to explain the multi-wavelength variability patterns [66]. We now appear to be at a healthy stage in blazar studies, where the quality of the available observations exceeds theoretical interpretations. The data quality will further improve in the coming years as continuous monitoring with survey instruments such as HAWC (and, to a lesser extent, dedicated monitoring with FACT) will help to catch high energy flares and to better characterize the temporal variability.

Gamma-ray emission from blazars can also be used as a probe of the intensity of the extra-galactic background light (EBL), due to the absorption of gamma-ray photons by pair-production. My co-rapporteur summarized published work by H.E.S.S. in which a clear detection ( $8.8\sigma$ ) of the imprint of the EBL was detected in a stacked analysis of 75,000 gamma-ray photons from 7 bright blazars with  $z < 0.19$  [67]. The most exciting new results in this area at the ICRC concerned two sources at the gamma-ray horizon. Hubble

Space Telescope observations of hydrogen line absorption features in the optical spectrum of PKS 1424+240 have been used to place a firm lower limit on its redshift of  $> 0.6035$ , making this the most distant TeV source to be detected [68]. The results of new VERITAS observations of this source were shown [69], as were MAGIC observations of another very distant TeV blazar, PG 1553+113, at  $z > 0.4$  [70]. For PG 1553+133, spectral curvature is observed, which can be explained as due to the energy dependent absorption by the EBL. For both PG 1553+133 and PKS 1424+240, the intrinsic spectra, corrected for absorption effects, appear unusually hard, with some indication of an upturn at the high-energy end of the spectrum. The strength of this feature depends on the EBL model which is applied, however, and stronger conclusions could be drawn with both better statistics at the highest energies and a firm redshift determination for each source.

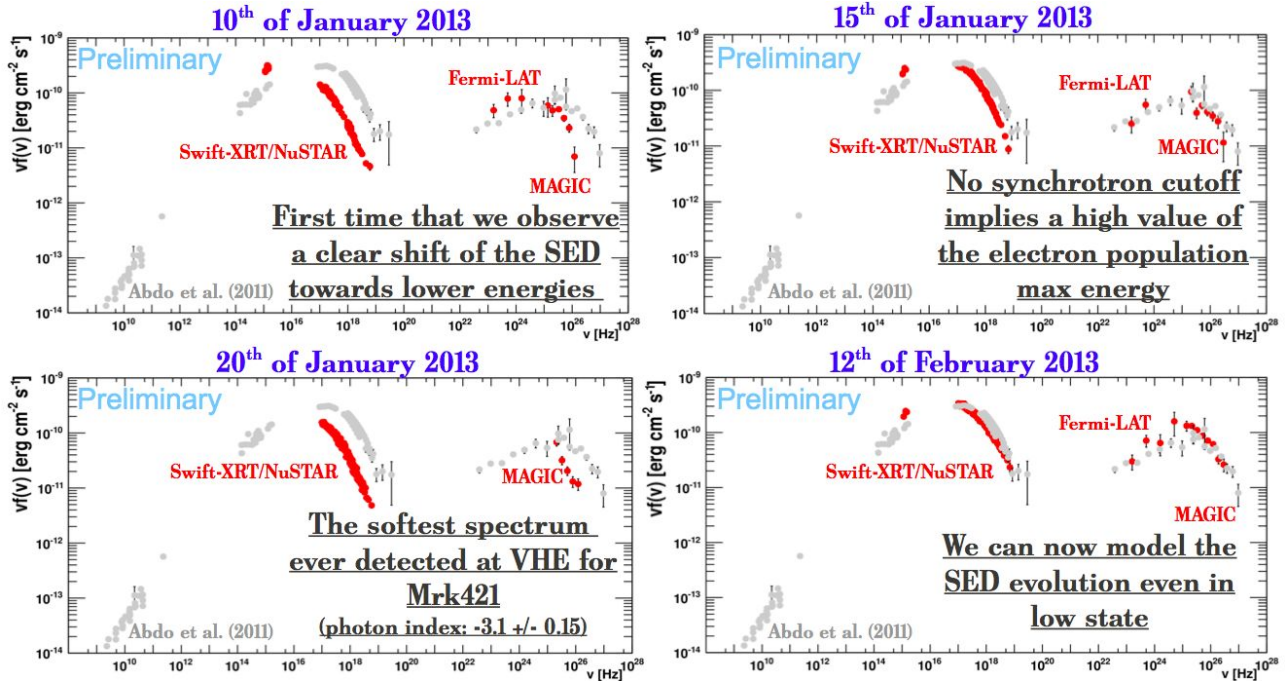
Flat-spectrum radio quasars (FSRQs) are almost as common as BL Lac objects in the Fermi catalog, but comprise only a small subset of extragalactic TeV sources (3 objects), due to their soft, steep spectra and generally larger distances. MAGIC observations of PKS 1510-089 resulted in a confirming detection of this source, first detected by H.E.S.S. [66, 71], while 3C 279, the first, and most distant ( $z = 0.5362$ ) FSRQ to be detected at TeV energies, has also been re-observed, but not detected. The origin of the TeV gamma-ray flares, and the correlation between the TeV emission and emission at other wavelengths, remains poorly defined for these sources.

### Radio Galaxies

Observations of nearby radio galaxies, in which the jet is not directly oriented towards the line-of-sight, are also of high priority for the TeV observatories. In particular, these allow attempts to correlate TeV emission properties with changes in the internal structure of the jet, which can be resolved at other wavelengths.

IC 310 was originally classified as a head-tail radio galaxy, a class of objects characterized by their extended jets which point in a direction determined by the galaxy's motion through an intra-cluster medium. High energy emission was detected from this object by Fermi above 30 GeV, and during MAGIC observations in 2009/10, as reported at the time of the last ICRC [73, 74]. Since then, a one-sided blazar-like compact radio jet has been identified in VLBI radio observations, which argues against the head-tail classification, and suggests that IC 310 may instead be the closest known blazar ( $z = 0.0189$ ). MAGIC observations in November 2012 detected an exceptionally bright flare, lasting less than one day and reaching a level in excess of half of the Crab Nebula flux above 1 TeV [75] (Figure 13). The TeV spectrum during the flare is unchanged, and radio monitoring does not yet, at the time of this meeting, show any response of the radio jet to the gamma-ray flare. Monitoring continues, at radio and other wavelengths, since the typical timescale between a gamma-ray flare and the ejection of new radio components may be several months or longer.

Separated from IC 310 by just  $0.6^\circ$  on the sky is the central dominant galaxy of the Perseus cluster, NGC 1275. With a visible counter-jet, NGC 1275 is one of only three, non-blazar AGN detected above 100 GeV (the others being M 87 and Cen A) [76]. The power-law source spectrum breaks sharply at GeV energies, becoming one of the softest spectrum sources to be detected from the ground at higher



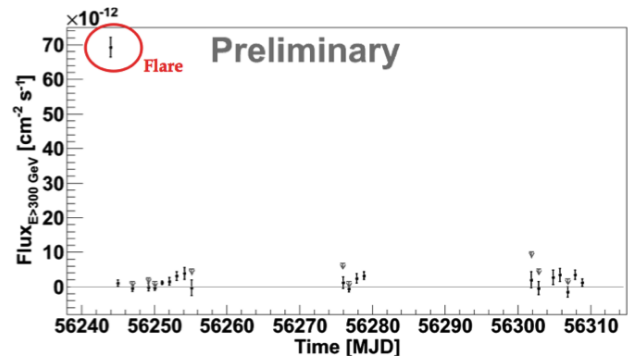
**Figure 12:** Daily measurements of Markarian 421 in different states in 2013, including the first contemporaneous observations with NuSTAR, which observes in the 3-79 keV energy range [64]. The grey points show an average spectrum from [72]

energies ( $\Gamma \sim -4.0$ ). A confirming detection of the source with VERITAS was only possible following a substantial reduction in the energy threshold of the upgraded instrument [11]. Long term monitoring at TeV, GeV, optical and radio wavelengths was also presented at this conference and shows correlated emission between the optical flux and that above  $> 100$  MeV [77], suggesting a common point of origin in the core of the AGN. The broadband spectrum is well-described by a simple one-zone synchrotron self-Compton model, as might be expected for a BL Lac type object with a misaligned jet.

By far the most well-studied of the TeV radio galaxies is M 87, which is easily visible from both the Northern and Southern hemispheres. No new results were shown at this meeting, but a summary of 10 years of observations with gamma-ray and multiwavelength partners illustrates that, despite the exceptionally rich dataset, a unique signature linking TeV emission with flares or jet structures at other wavelengths is still yet to be established [78, 79].

### Other results in Astroparticle Physics

Ground-based gamma-ray observations have been used in a variety of sometimes innovative ways to address other questions in astroparticle physics, fundamental physics and cosmology. At this meeting, a search for modifications to the intrinsic gamma-ray spectrum of the bright blazar PKS2155-304 was used to constrain the strength of the coupling of axion-like particles to photons [80]. An analysis of the full H.E.S.S. data archive was used to improve the upper limit on the local rate of primordial black hole explosions by almost an order of magnitude, to  $< 1.4 \times 10^4 \text{ pc}^{-3} \text{ yr}^{-1}$  [81]. Searches for evidence of Lorentz invariance violation have customarily focussed on transient events, such as blazar flares or gamma-ray bursts, but pulsars also provide a high-

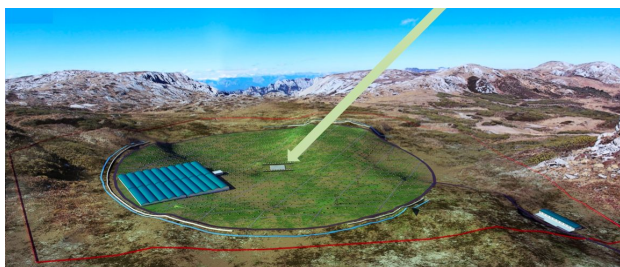


**Figure 13:** The TeV lightcurve of IC 310, showing a bright flare ( $> 0.5$  Crab) detected in November 2012 [75].

energy photon flux with a sharp temporal profile. The VERITAS collaboration have exploited their observations of the Crab pulsar to constrain the energy scale of Lorentz invariance violations to  $> 3 \times 10^{17}$  GeV [82]. The sensitivity of the full HAWC observatory to address questions of this nature has also been studied, with promising conclusions [83, 84].

The changing scientific priorities in astroparticle physics warranted the creation of a dedicated dark matter (DM) sessions for this meeting, distinct from the gamma-ray sessions. DM submissions, including indirect detection techniques, were comprehensively reviewed by the DM session rapporteur. Results related to ground-based gamma-ray instruments include new limits on WIMP annihilation cross-sections from observations of dwarf spheroidal galaxies [85, 86, 87], along with the description of new analysis techniques for such datasets [88]. Methods for “stacking” the results from observations of multiple source candidates holds promise, and may alleviate the potential for system-





**Figure 14:** A schematic view of the proposed LHAASO array. See text and Cao et al. [92] for details.

atic errors associated with extremely long exposures on a single field-of-view. The development of statistical methods to achieve this can also spread the observing load over multiple instruments, and allow to factor in complementary information from adjacent wavebands. Observations of a Fermi-LAT dark matter subhalo candidate were also described [89], as was a search for the signature of decaying DM [90] and the potential for detecting Q-balls with HAWC [91].

## The Future

Major upgrades to all of the current generation of IACTs have recently been completed, and new facilities are now in the prototyping and advanced planning stages. This growth in development activity was reflected at the ICRC in a large number of detailed technical presentations, many of which were presented in the poster sessions.

The Large High Altitude Air Shower Observatory (LHAASO) collaboration are proposing an ambitious survey instrument to study both cosmic rays and gamma-rays, which builds on the success of the ARGO-YBJ and Tibet arrays (Fig. 14) [92]. The first phase of this project will consist of:

- A  $1 \text{ km}^2$  array of 5635,  $1 \text{ m}^2$  scintillator detectors, with 15 m spacing, for electromagnetic particle detection [93]
- An overlapping  $1 \text{ km}^2$  array of 1221,  $36 \text{ m}^2$  underground water Cherenkov tanks, with 30 m spacing, for muon detection [93]
- A close-packed, surface water Cherenkov detector facility with a total area of  $90,000 \text{ m}^2$ , four times that of HAWC
- 24 wide field-of-view air fluorescence (and Cherenkov) telescopes
- 425 close-packed burst detectors, for high energy secondary particles near the centre of the array

Various prototyping studies of the different detector components and associated instrumentation were presented at the ICRC, including the successful demonstration of a small engineering array at Yangbajing. A site for the full array has been selected at Shika, close to Yangbajing, and at a similar altitude of 4300m above sea level. The project still has some remaining administrative hurdles to cross but, once funding is secured, construction will begin (in 2014), and last approximately 5 or 6 years. Also in the realm of the

survey instruments, possible “third generation” successors to HAWC were discussed, with potential improvements including higher altitude, larger active collection area, separate measurement of electromagnetic and muon components of the shower, and a southern hemisphere site to improve access to the Galactic Center region [95].

The most advanced development activities towards a next generation ground-based gamma-ray telescope were shown by the Cherenkov Telescope Array (CTA) collaboration, with around 60 presentations at this ICRC. Almost the entire international ground-based community has now united behind this effort, and the project has moved on significantly since the last ICRC. I will briefly list some of the major advances; Jim Hinton’s review talk at this conference on the status and future of gamma-ray astronomy also contains more information on CTA [2].

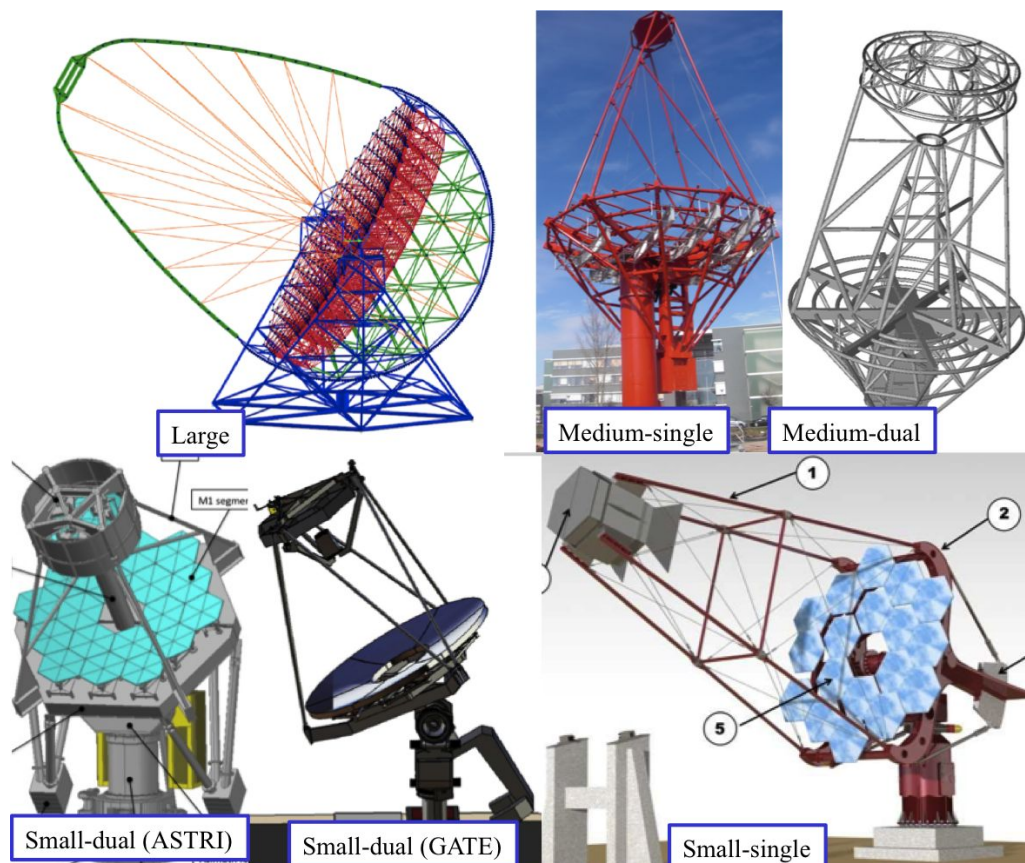
CTA is planned to consist of a large array in the southern hemisphere and a smaller array in the north. The sites have been evaluated for their suitability for Cherenkov observations using a variety of different sky and environmental monitoring tools [96, 97, 98]. At the time of writing, formal negotiations on two sites in the south (in Namibia and Chile) are underway, with an Argentinian site [99] in reserve as a third option. No decision has been made regarding the northern site, but various candidates have been proposed at locations in Spain [100], Mexico and the USA [101].

The arrays themselves will be comprised of telescopes of multiple different designs, to optimize the sensitivity and to provide the widest possible coverage in energy (Figure 15). At the center of the array will be four “Large Size Telescopes” (LSTs) [102], with reflector dish diameters of 23 m, optimized for  $\sim 20 - 200 \text{ GeV}$ . The design for these telescopes is based upon the successful MAGIC design, scaled up in size, but down in weight and cost, through the application of new technologies and materials. The camera will consist of 2000 super-bialkali PMTs, read-out using the DRS4 analog memory ASIC [103, 104].

“Medium Size Telescopes” (MSTs), will provide deepest coverage of the mid-range of energies, centered around 1 TeV. Two designs are envisaged for the MSTs, both of which may be deployed. The first is a single reflector Davies-Cotton design, similar to the VERITAS and original H.E.S.S. telescopes, with a diameter of 12 m. The second is a novel dual-mirror design, using a Schwarzschild-Couder optical system, with a 9.5 m primary reflector. The single reflector MST exists in an advanced prototype form at the Adlershof test site near Berlin. The dual mirror version is under development and will be prototyped at the VERITAS site in Arizona [105].

The high energy range of the array, up to hundreds of TeV, will be covered by the “Small Size Telescopes” (SSTs). These telescopes, with an aperture of  $\sim 4 \text{ m}$ , will be the most numerous, and most widely spaced. Two dual-mirror designs [106, 107, 108], and one single mirror system [109] are in the prototyping stage, and will be tested at sites in Poland, Paris and Italy.

In parallel with the telescope structural design development, advanced prototyping and testing is underway in mirror designs [110], and telescope camera, trigger and data acquisition systems (e.g. [104, 111, 112, 113]). New technologies are being tested at all stages, both in order to enhance the array performance, and to deal with the necessities of mass production, low cost, and strict maintenance requirements. (e.g. dielectric mirror coatings, high quantum



**Figure 15:** A summary of the different telescope designs in development for CTA.

efficiency and multi-anode PMTs, silicon-based photodetectors, etc.). A significant effort is also being put into peripheral and monitoring systems and calibration efforts (e.g. [114, 115, 116]). Monte Carlo simulations [117] and data analysis tools are also well advanced, and are being used to inform design decisions, including the possible array layouts and the impact of different observatory locations (Figure 16).

## Concluding remarks

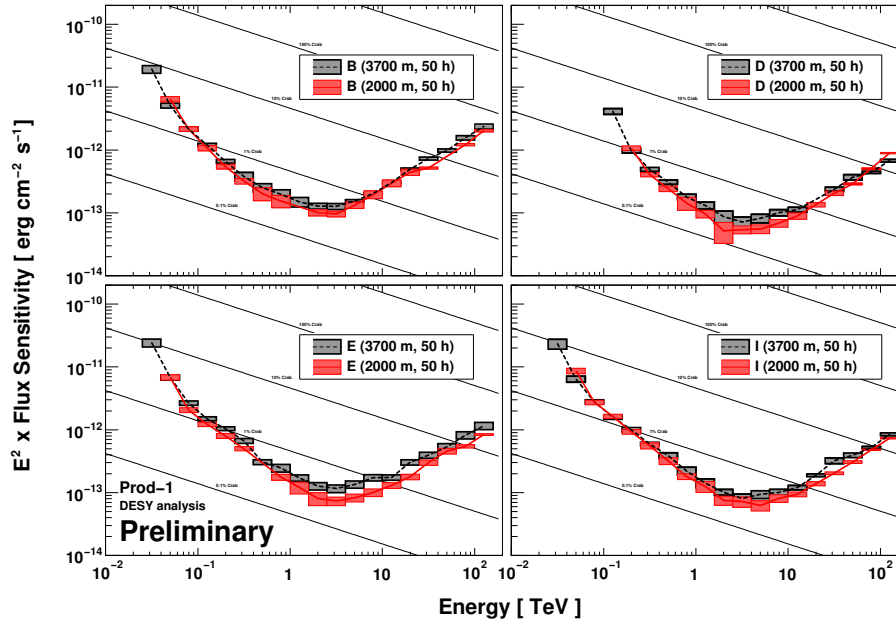
Every ICRC over the last decade has seen dramatic advances in ground-based gamma-ray astronomy, and this meeting was no exception. Although the high energy sky continues to surprise us, it would be fair to say that the most significant advances shown in Rio were in instrumentation, other than observational or theoretical. Upgrades to existing facilities, new facilities coming online, and intensive development work towards the next generation of instruments were all presented. The next ICRC will showcase the first fruit of these efforts and promises to mark another important step in the development of the field. I look forward to seeing you all there.

## Acknowledgements

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**Figure 16:** The differential sensitivity of for four candidate CTA array configurations at two different altitudes (red: 2000 m, black: 3700 m. Figure from [117].

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